Commonwealth Energy Biogas/PV Mini-Grid Renewable Resources Program

Making Renewables Part of an Affordable and Diverse Electric System in California

Contract No. 500-00-036

Photovoltaic & Biogas Generation Profiles

Project No. 1.1 Program Planning and Analysis

Task 1.1.8 Final Report

Prepared For:
California Energy Commission
Public Interest Energy Research Renewable Program

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research

For more information on the PIER Program, please visit the Commission's Website at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

For Commonwealth Program-specific information, please visit: http: //www.pierminigrid.org.

What follows is a comparison report for the California Energy Commission, Public Interest Energy Research Program, Contract Number 500-00-036, conducted by the Commonwealth Energy Team. The report is entitled, "*Photovoltaic & Biogas Generation Profiles*". This project contributes to the Renewable Energy Component of the PIER Program.

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Introduction

This report summarizes methods and findings of a study of the electric generation profiles of building-integrated photovoltaics (BI-PV) and biogas-based energy systems in California. The study was conducted by Itron, Inc. (Itron) for the California Energy Commission (Commission) under Contract No. 500-00-036 Task 1.1.8. This task is one element of the broader Commonwealth Energy Biogas/PV Renewable Mini-Grid Program (Program) being administered through the Commission's Public Interest Energy Research (PIER) group. The general, overall purpose of the broader Commonwealth Renewables Program is to increase the affordability of renewable energy in California through demonstration of new applications and quantification of energy and environmental benefits recognized by the market.

1.1 Overview of Commonwealth Program Planning and Analysis Project

The primary objectives of the Commonwealth PIER Program Planning and Analysis Project are to:

- Define the initial study area,
- Inventory the study area's potential photovoltaic and biogas resources to assess the potential of such resources and to identify potential demonstration projects,
- Identify a mini-grid where the potential impact of the development of such resources can be assessed,
- Conduct power flow studies to identify and quantify the benefits of renewable energy projects on the local electric distribution system,
- Identify and prioritize individual demonstration projects, and
- Identify cost savings and benefits that would accrue by developing complementary resources.

A multidisciplinary team led by Itron and supported by CH2MHill and the Renewable Energy Development Institute (REDI), is responsible for meeting these program-planning objectives. CH2MHill is responsible for undertaking the various biogas resource inventory assessments. Itron and REDI jointly develop estimates of BI-PV technical potential. Power flow and other studies related to the mini-grid are being undertaken by Zaininger

Engineering Company (ZECO). As mentioned above, the electric generation profiles documented in this report were developed by Itron.

1.2 Electric Generation Profiles

The purpose of this task is to develop electric generation profile information that will ultimately support estimation of possible impacts on the electric grid of BI-PV and biogas development in the mini-grid area. In addition to generation profiles, this report includes an assessment of the flexibility of each generation profile based upon: 1) proposed program, and 2) fully realized mini-grid market potential.

The generation profiles presented in this report describe the shape of charts depicting power output versus time. Estimation of impacts on the electric grid will require combining the generation shape information with estimates of market potential yielded by Task 1.1.7, Assess Electricity Market Potential (MW's) of biogas and commercial PV within the mini-grid region. This synthesis of sub-task results will be accomplished using power flow modeling that will be completed under Task 1.1.9 of the Program Planning and Analysis Project.

1.3 Report Organization

Both hourly and seasonal average generation profiles were developed for BI-PV and Biogas resources. The BI-PV profiles are described in Section 2, while the Biogas profiles are covered in Section 3. Hourly generation profiles are saved electronically in a MS Access database. The structure and content of this database are summarized in Appendix A.

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PV Generation Profiles

The Task 1.1.8 analytical activities and results related to PV resources are summarized in this section.

2.1 Overview

Separate results were calculated for crystalline and amorphous PV material, and for a variety of fixed array tilts (horizontal to vertical in 15 degree increments) and compass orientations (45 degree increments). Generation profiles were also estimated for 1- and 2-axis tracking systems. The 1-axis results are based on rotation of PV arrays about a horizontal, N-S axis. This type of configuration might possibly find application in parking shade structures.

Hourly generation profiles for a total of 104 different cases were estimated, as summarized in Table 2-1. In most cases, each hourly profile value represents an estimate of the PV system AC power output for a PV system sized to produce 1.0 kW under PTC[1] conditions (i.e., 1.0 kW AC-PTC). The composite generation profiles represent weighted averages of assumed mixes of systems described in a later section; these profiles are expressed in units of kW. The resulting hourly PV generation profiles are saved in a MS Access database. A description of the format and content of the database of PV Generation Profiles is included as Appendix A.

Table 2-1: Summary of PV Generation Profile Characteristics

PV Type	Orientation/Basis	Number of Generation Profiles
Amorphous & Crystalline Silicon	Horizontal	2
	Tilt: 15/30/45/60/75/90 deg. Azimuth: N/NE/E/SE/S/SW/W/NW	96
	1- and 2-axis tracking	4
Composite	PIER Commonwealth BI-PV Project	1
Composite	Mini-Grid Market Potential	1
Total		**104**

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[1] PTC conditions comprise 1,000 W/m^2 plane-of-array solar radiation, 20 °C ambient temperature, and wind speed equal to 1 m/s.

2.2 Data Sources

For a given PV system, the power output during any hour is sensitive to weather and to several key performance characteristics of the PV material and system. The several key data sources used in the PV generation profile analysis are identified below and described in the following sections.

- TMY2 Weather Data,
- Sandia PV System Performance Research, and
- California Energy Commission PV Research.

TMY2 Weather Data

The U.S. Department of Energy's National Renewable Energy Laboratory has sponsored development of a National Solar Radiation Database. This database has been used to create hourly, typical-year weather data files for 239 locations throughout the United States. Typical meteorological year ambient temperature and solar radiation data for Los Angeles were used in this analysis. Beam and diffuse solar radiation data were used in calculations of plane-of-array solar radiation, while ambient temperature was used in the calculation of PV system performance adjustment factors.

Sandia PV System Performance Research

PV module power output may be sensitive not only to geometric "cosine" effects[2] that influence the intensity of beam radiation striking the module surface, but also to other angle of incidence (AOI) effects related to reflectivity or other factors. Sandia National Laboratories has studied these other angle of incidence effects and published results in terms of an AOI Factor that summarizes the influence of angle of incidence on PV power output. Data presented in a Sandia report (King, 2002) were used to fit a curve relating AOI Factor to angle of incidence, where the angle of incidence is the angle between the beam radiation on a surface and the normal to that surface. The result is depicted graphically in Figure 2-1. The AOI Factor values for crystalline and amorphous PV material are similar so a single AOI Factor curve is used in the analysis.

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[2] The term 'geometric cosine effect' refers to a relationship between the intensity of beam radiation striking PV modules (and hence their power output) and the angle between that beam radiation and a line perpendicular to the PV module surface (i.e., angle of incidence). As the incidence angle increases above zero degrees (where the cosine is equal to 1), the intensity of beam radiation varies as the cosine of the angle of incidence.

Figure 2-1: Angle of Incidence Factor

PV module power output may be sensitive not only to atmospheric diminution attributable directly to atmospheric scattering of solar radiation by the atmosphere, but also to other solar altitude effects related to solar spectrum variability. The extent of atmospheric scattering (and hence solar spectrum shifts) is related to the air mass[3] through which solar radiation travels from the sun to the earth's surface. Sandia National Laboratories has studied these other solar altitude effects and published results in terms of an Air Mass Factor that summarizes the influence of air mass on PV power output. Data presented in the Sandia report (King, 2002) were used to fit a curve relating Air Mass Factor to Sun Elevation Angle. The result for amorphous PV material is depicted graphically in Figure 2-2. For crystalline PV material the Air Mass Factor is assumed equal to 1 for all sun elevation angles.

Figure 2-2: Air Mass Factor (Amorphous PV Material)

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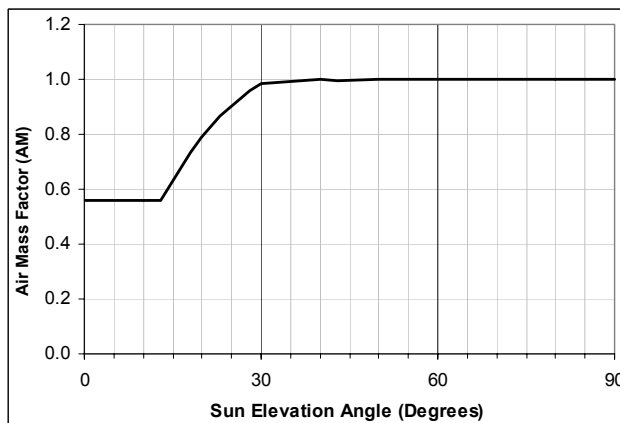
[3] Air mass is used to describe the relative length of the path that the sun's rays traverse through the atmosphere before reaching the ground. An AM=1 condition occurs when the sun is directly overhead at a sea level site; AM values of 10 or greater occur near sunrise and sunset.

California Energy Commission PV Research

The California Energy Commission has supported recent research concerning the performance of PV systems installed in the residential sector. Included in this work was an investigation of relationships between ambient weather conditions and PV module temperature. Findings of this work were used in the calculation of adjustment factors used to incorporate temperature effects into the analysis.

2.3 Analytic Methodology

The TMY2 data were used in combination with solar radiation models from a solar engineering textbook (Duffie & Beckman, 1991) to calculate hourly estimates of plane-of-array solar radiation. A ground reflectivity of 0.2 was assumed in the Perez diffuse solar radiation model calculations. Results of the solar geometry calculations were adjusted to incorporate angle-of-incidence and solar spectrum effects that influence photovoltaic system performance. Adjusted plane of array solar radiation results were used in PV module temperature and PV system power output calculations.

The angle-of-incidence factor AOI from Figure 2-1 was applied to the beam component of solar radiation only. Strictly speaking, available data suggest use of different adjustment factors for crystalline silicon (c-Si) and amorphous silicon (a-Si) PV materials, but the difference is relatively small in the context of the other sources of uncertainty and variability in this analysis so a single AOI adjustment curve was used for both c-Si and a-Si.

The air mass factor AM from Figure 2-2 was applied to both the beam and diffuse components of solar radiation. For c-Si the factor is relatively minor so is neglected. The estimate of total effective solar radiation on the tilted plane of the array was calculated as:

$$I_e = AM \times \left(I_b \times AOI + I_d + I_r \right)$$

Where:

I_e = Total effective solar radiation on the tilted plane of the array

I_b = Beam solar radiation on the tilted plane of the array

AOI = Angle-of-Incidence Factor

AM = Air Mass Factor

I_d = Diffuse solar radiation on the tilted plane of the array

I_r = Reflected solar radiation on the tilted plane of the array

Next, for each hour an initial estimate of power output was calculated for a 1.0 kW AC-PTC PV system. The initial estimate of power output accounted for the actual, effective solar

radiation during the hour, but did not account for temperature effects. The initial estimate of power output was calculated as:

$$PV_i = \frac{I_e}{I_{PTC}}$$

Where:

PV_i = Initial estimate of PV system power output

I_{PTC} = Total solar radiation on the tilted plane of the array for PTC

conditions (i.e., 1,000 W/m^2)

The actual module temperature for each hour was estimated by adjusting from the PTC module temperature depending on ambient temperature and plane-of-array solar radiation, based on the following assumptions:

- Power is produced only when solar radiation exceeds 30 W/m^2,

- Module temperature is 48.5 °C at PTC conditions (i.e., 20 °C ambient, 1,000 W/m^2),

- A drop from 1,000 to 900 W/m^2 yields a drop in module temperature of 3.4 °C,

- An increase in ambient temperature from 20 °C to 37.8 °C yields an increase in module temperature of 20.2 °C,

- PV module temperature is never less than ambient temperature,

- 1 °C increase in crystalline module temperature yields a 0.5% power output decrease, and

- 1 °C increase in amorphous module temperature yields a 0.25% power output decrease.

The final estimate of PV system power output was calculated as:

$$PV = PV_i \times (1 + TEMP)$$

Where:

PV = Final estimate of PV system power output

$TEMP$ = Power output factor accounting for module temperature effects

2.4 Results

Hourly PV generation profiles are saved in the MS Access database accompanying this report. A description of the layout of the database is included as Appendix A. Annual

energy production results are summarized in Table 2-2 for several of the 102 separate PV system scenarios included in the analysis.

Table 2-2: Annual Energy Production for Typical Crystalline Configurations

Tilt (Degrees)	Azimuth	Annual Energy (kWh/Year)
0	N/A	1909
15	South	2080
30	South	2141
90	South	1332
15	East	1835
30	East	1704
90	East	990
15	West	1906
30	West	1823
90	West	1115
1-Axis Tracking	N/A	2470
2-Axis Tracking	N/A	2730

Variability in average seasonal power output is depicted graphically in Figure 2-3 for several typical tilt-orientation cases. The "Winter" curve is based on data for December through February, while the "Summer" curve is based on data for June through August. In these charts, hour of day is based on clock time as opposed to standard time (i.e., the times represent Daylight Savings Time in the summer).

Figure 2-3: Graphical Summary of PV Generation Profiles for Several Typical Cases
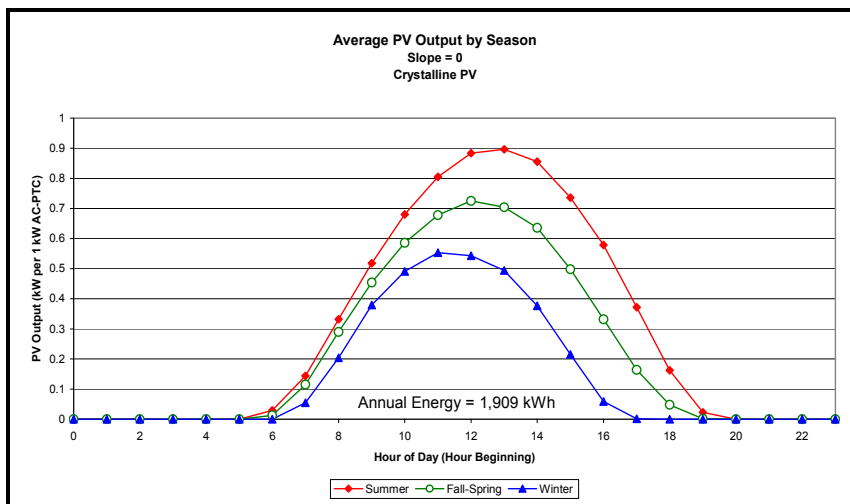
Figure 2-3: Graphical Summary of PV Generation Profiles for Several Typical Cases (Continued)
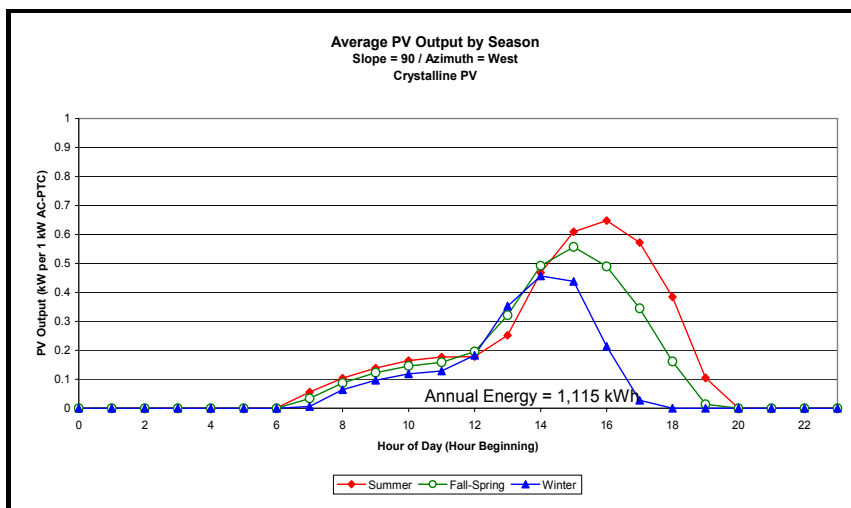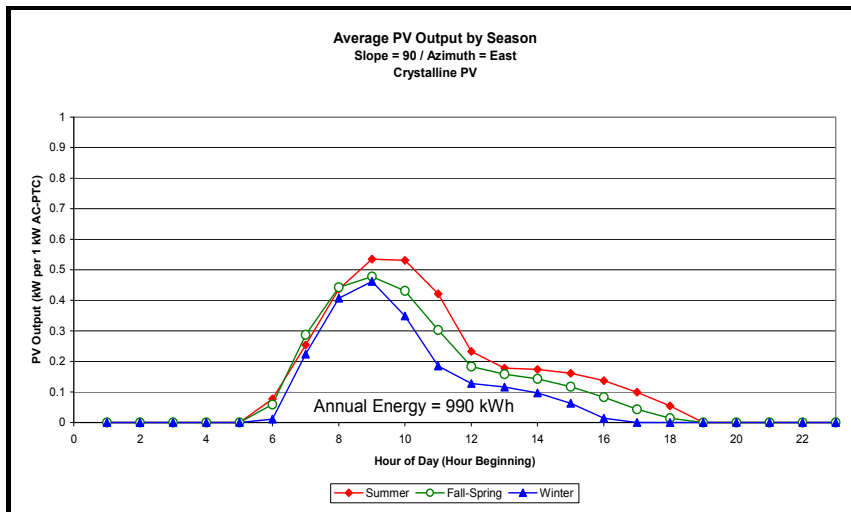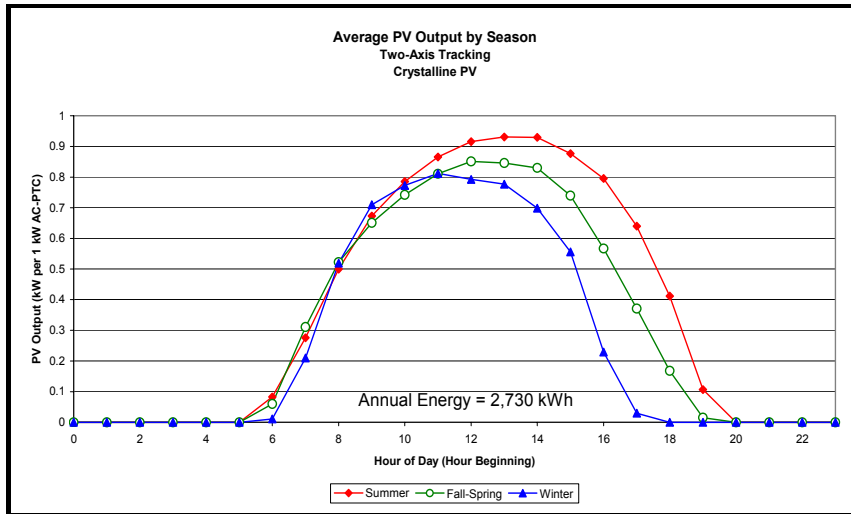
For purposes of supporting subsequent power flow modeling it is necessary to estimate the shape of a single, composite generation profile corresponding to BI-PV Market Potential. The shape of the composite generation profile will be directly related to assumptions concerning the mix of configurations and technologies of the population of developed projects. Composite characteristics assumed for this analysis are summarized in Table 2-3.

Table 2-3: Assumed System Characteristics - Mini-Grid Market Potential

Tilt (Degrees)	Azimuth	BI-PV Material	Portion of Mix (%)
0	N/A	Crystalline	60%
15	South	Crystalline	25%
90	South	Amorphous	5%
1-Axis Tracking	N/A	Crystalline	10%

A composite BI-PV generation profile was calculated using the characteristics summarized in Table 2-3. The calculation was normalized such that hourly PV power output values represent power production per unit of installed PV capacity. Results of the analysis are summarized graphically in Figure 2-4. The per-unit annual energy production for the composite generation profile is 1,972 kWh/year per 1.0 kW AC-PTC of photovoltaic system capacity.

Figure 2-4: Generation Profile (Normalized) – Mini-Grid BI-PV Market Potential
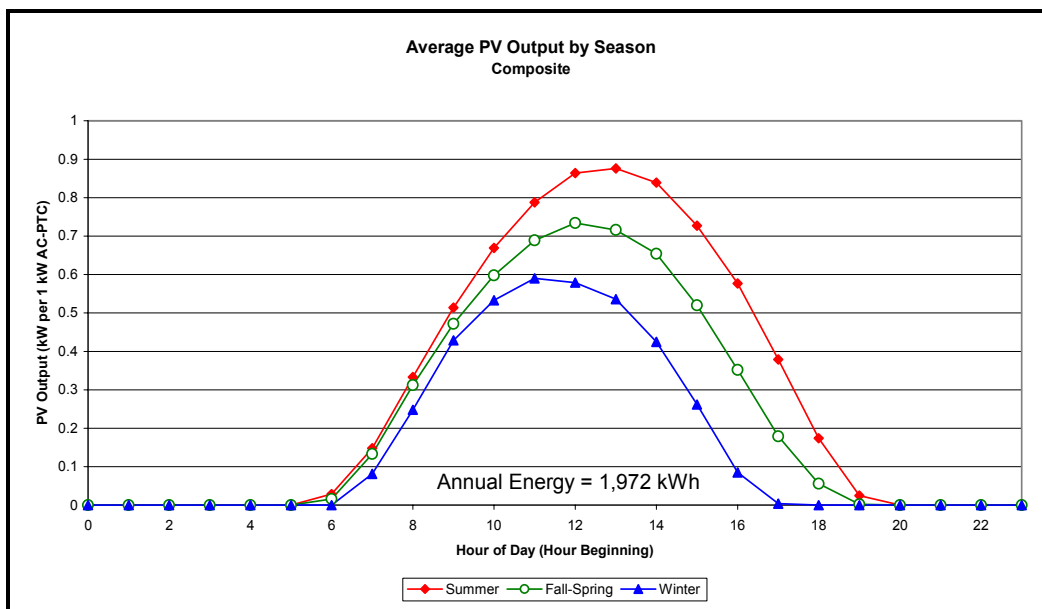
To develop a market-potential composite BI-PV generation profile for the study period the shape information illustrated in Figure 2-4 was combined with results of the analysis of market potential magnitude. The cumulative mini-grid BI-PV market potential estimated for years 2003 through 2012 ranged from 685 kW to 19,460 kW. The estimate of annual energy production per unit of installed capacity is 1,972 kWh, as indicated in Figure 2-4. Resulting energy production and installed capacity trends for the Market Potential study period are summarized in Figure 2-5.

Figure 2-5: Generation Profile Summary – Mini-Grid BI-PV Market Potential
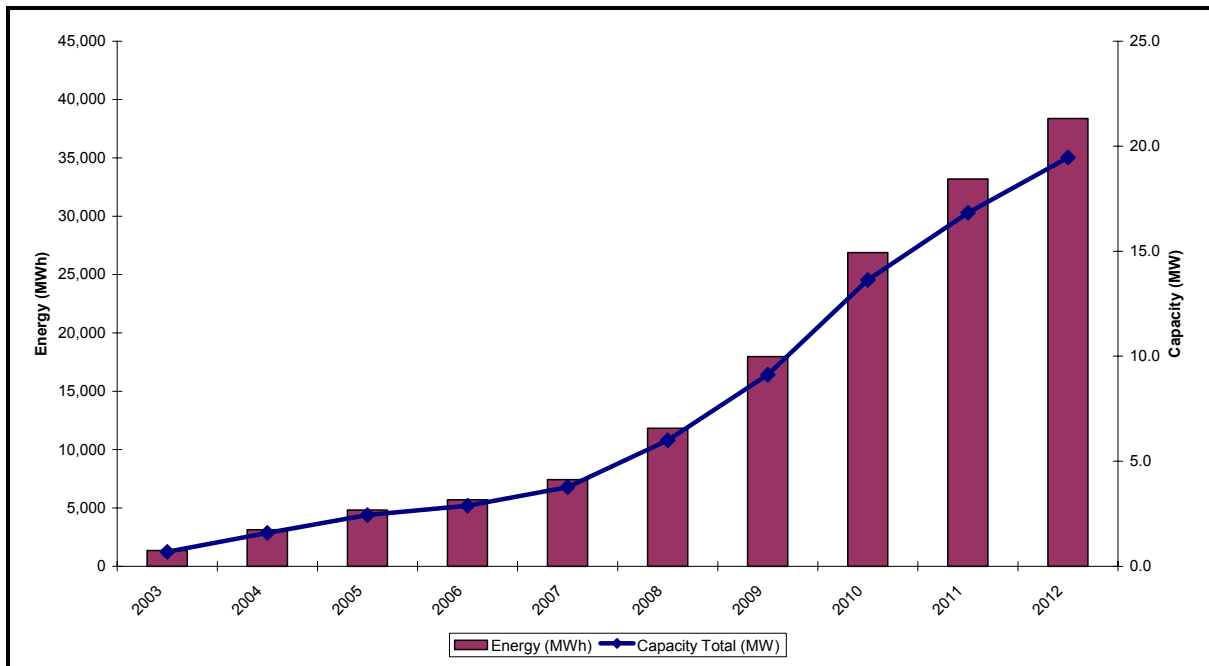
Characteristics of BI-PV systems actually installed through the PIER Commonwealth BI-PV Program differ from those presented in Table 2-2. The characteristics of the five BI-PV systems, which are expected to be installed through the program, are summarized in Table 2-4 on the following page. None of the systems utilize tracking.

Table 2-4: Actual System Characteristics – PIER Commonwealth BI-PV Program

System No.	System Size (kW)	PV Material	Orientation & Tilt	Installation Date
#1	1,000	Amorphous	Horizontal	July 1, 2004
#2	100	Amorphous	Horizontal	September 1, 2004
#3	50	Crystalline	South @ 30º tilt	September 1, 2004
#4	40	Crystalline	20 kW @ South & 35º tilt 20 kW @ West & 35º tilt	September 1, 2004
#5	21	Crystalline	24º W. of S. & 7º tilt	April 1, 2004
	21	Hybrid	24º W. of S. & 12º tilt	
	9	Amorphous	Horizontal (approx.)	
	12	Crystalline	Horizontal (approx.)	

The generation profiles corresponding to BI-PV systems actually installed through the program are summarized in Figure 2-6, which presents seasonal average generation profiles for the BI-PV systems expected to be installed through the program.

Figure 2-6: Generation Profile (Normalized) – PIER Commonwealth BI-PV Program
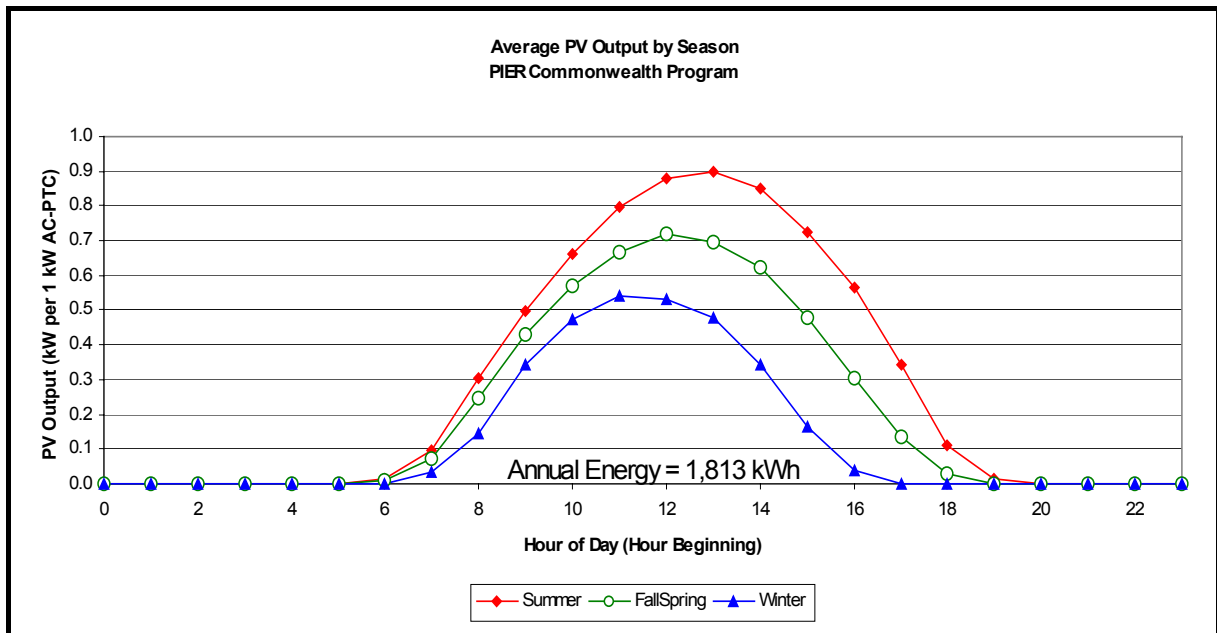
The energy production and installed capacity trends corresponding to Project 3.3 activities under the PIER Commonwealth BI-PV Program are illustrated in Figure 2-7 for the Program period.

Figure 2-7: **Generation Profile Summary – PIER Commonwealth BI-PV Program**
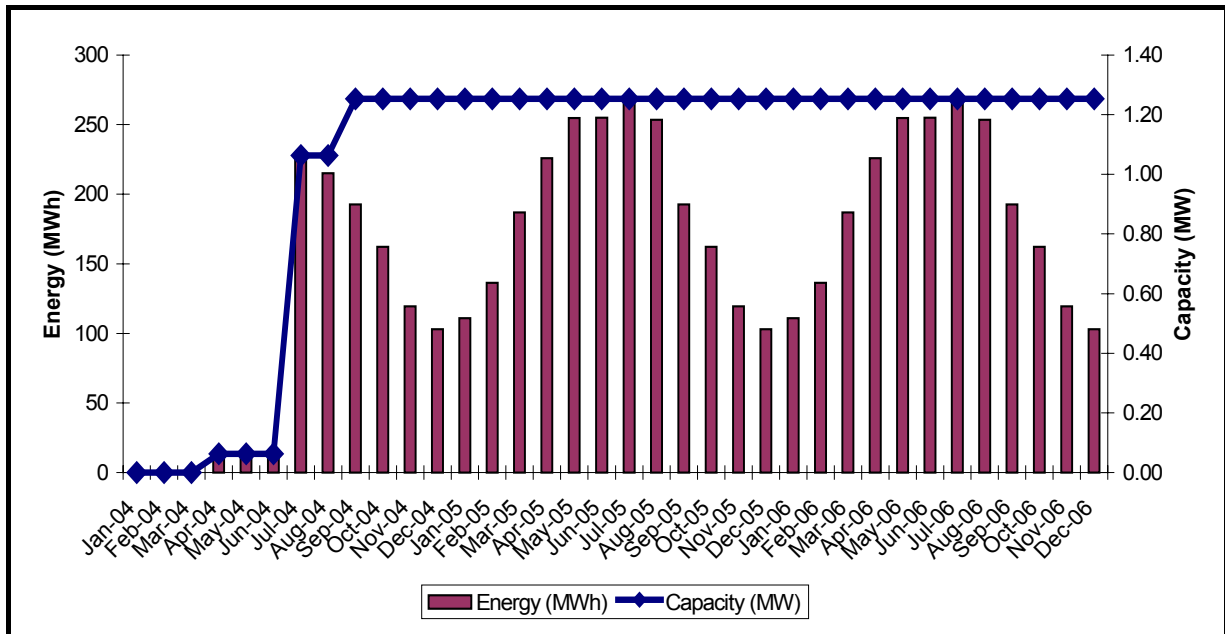
Flexibility of Generation Profiles

For the proposed program, BI-PV applications that may be considered for development include: roof-integrated, awnings, carports, covered walkways and shade structures, curtain walls, skylights and "direct" applications such as water pumping. There are at least two principle ways in which the program-level generation profile yielded by individual projects could be shaped. First, the orientation and other characteristics of individual projects can be selected in such a manner as to produce a desired program-level load shape. Second, battery storage could be added to some or all of the systems to substantially increase control over both project- and program-level PV generation profiles.

If sufficient battery storage capacity is included in PV system design, a substantial degree of control over the PV generation profile may be achieved. Most commonly, battery storage is sized such that loads can be satisfied during periods of cloudy or stormy weather. For on-grid systems, battery storage is typically sized to provide some degree of instantaneous UPS, as well as some level of ongoing support of some critical loads or even all loads.

To date, batteries have not been widely used to control generation profiles across seasons. In the future, however, other energy storage approaches (e.g., electrolysis of water into hydrogen gas) may be combined with emerging energy conversion technologies (e.g., fuel

cells), to yield a considerable degree of control over PV generation profiles. These emerging technologies may even allow some degree of flexibility where storage of solar energy across seasons is concerned.

For this program, PV systems that are strictly grid-tied and that do not include provisions for energy storage are envisioned. Therefore, the flexibility of PV generation profiles for both the program and the fully-realized mini-grid market potential are governed by the distribution of PV system capacity across the possible tilts, orientations, and PV material types. The assumed basis of the composite PV generation profile was summarized in Table 2-3.

2.5 Discussion of Results

Key aspects of the basis, magnitude, and embedded assumptions are described briefly below.

Basis of Normalizing System Size

These generation profiles do not provide guidance on estimating system losses necessary to translate cumulative nominal PV module direct current power output capacity under standard test conditions (DC-STC[4]) into PV system size (AC-PTC). This would be a critical step necessary to use the results of this analysis to predict the power output of any particular PV system. Information concerning the relationship between nominal PV module capacity and PV system size is available from a variety of sources (Wiese 2002, Scheuermann 2002).

Comparison to Other Findings

In this section, results of the analysis are compared to PV system performance estimates yielded by the PVWatts on-line tool, and PV system performance estimates described in a previous BI-PV market potential assessment.

PVWatts

Results estimated in this analysis are expressed in terms of PV system power output per unit of AC-PTC PV system size. When using PVWatts, the basis of system size entered into the program must be AC-STC PV system size. The question then becomes: What PVWatts system size corresponds with 1.0 kW of AC-PTC system size? A system sized to produce 1.0 kW AC-STC will produce less than 1.0 kW when the temperature warms up to PTC. Therefore, PVWatts must be used with a system size value somewhat larger than 1.0 kW if the resulting annual energy estimates are to be compared directly to results of this analysis. If PTC power output is assumed equal to 90% of STC power output then that system size is calculated as 1/0.9=1.11 kW.

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[4] STC conditions comprise 1,000 W/m^2 plane-of-array solar radiation, 25 °C cell temperature, and solar spectral irradiance per ASTM (air mass = 1.5).

Approximate PVWatts energy production estimates per kW of AC-PTC are summarized in Table 2-5 for several typical tilt-orientation combinations. These results are for crystalline silicon photovoltaic material. For each case, the PVWatts annual energy production estimate is less than the Itron estimate. The magnitudes of the differences range from 2% to 8%.

Table 2-5: Comparison of Itron and PVWatts Results for L.A. TMY2 Weather Station (Per 1.0 kW AC-PTC)

Tilt (Degrees)	Azimuth	PVWatts Annual Energy (kWh/Year)	PVWatts vs. Itron Comparison (Δ%)
0	N/A	1812	-5%
15	South	1995	-4%
30	South	2058	-4%
90	South	1227	-8%
30	East	1601	-6%
30	West	1739	-5%
1-Axis Tracking	N/A	2417	-2%

Some of this difference may be attributable to the STC to PTC factor, or to different assumptions for module temperature at PTC conditions, or to differences in the solar radiation models.

BI-PV Market Potential Study

A BI-PV Market Potential Study included information concerning the relative energy production for systems of various tilt-orientation configurations (A.D. Little 1995). These results, which are based on PVFORM modeling of PV system performance, are summarized in Table 2-6. Results of this analysis are similar to those reported by A.D. Little.

Table 2-6: Relative Annual PV Energy Production Versus Configuration

Tilt, Orientation	A.D. Little	Itron
Latitude Tilt, South	0% (baseline)	0%[5]
15 Deg. Tilt, South	4% Loss	3% Loss
Vertical, South	34% Loss	38% Loss

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[5] Differences for Itron are calculated with respect to results for tilt of 30 degrees, instead of for latitude tilt. Results should be close enough for this crude check of reasonableness because the latitude is approximately 34 degrees in L.A.

Simplifying Assumptions

Several simplifying assumptions that may limit the use of resulting load shapes or may require some measure of qualification or caveat are described below.

Assumption of a Single Temperature for PTC Conditions.

The temperature adjustment factors are median results for a sample of 19 residential systems. For systems mounted flush to an existing roof the temperature effects would probably be more pronounced, and free standing arrays would probably operate somewhat cooler. Module temperatures at PTC conditions are likely to be sensitive to system design.

Use of Los Angeles TMY2 data

Use of Los Angeles TMY2 data is a simplification because the mini-grid is located approximately 50 miles east of Los Angeles. Coastal weather effects influencing LAX ambient temperatures and solar insolation will cause the Mini-Grid and LAX generation profiles to be somewhat different. This difference represents one source of error in a broader project, one of the primary areas of emphasis of which is estimation of overall economic and environmental benefits attributable to BI-PV market potential in the Mini-Grid. Use of LAX weather may tend to overestimate demand-related benefits on the hottest days, and underestimate overall energy-related benefits. These effects tend to offset, and the magnitude of the net difference is substantially smaller than the magnitudes of error corresponding to other elements of the project. Other sources of project uncertainty include:

- Uncertainty in market penetration rates
- Uncertainty in forecasts of economic conditions
- Uncertainty in estimates of the distribution of PV system orientations

Given the magnitude of weather-related error in comparison to other sources of uncertainty, LAX TMY2 weather data yield sufficiently accurate results for this project. Other projects under the PIER Commonwealth BI-PV Program involve assessment of economic feasibility of particular BI-PV systems. For these analyses more accurate weather data will be required. Mini-Grid TMY data will be developed in the future to support these technical and economic analyses of particular BI-PV systems.

2.6 Conclusions

Hourly PV generation profiles were estimated for 104 tilt-orientation-material combinations and two additional composites, and the data were saved in a MS Access database. The method used to develop the profiles was relatively simple, however results are in general agreement with information available from other sources. Finally, use of the generation

profiles to estimate power output for a particular system would require estimation of the AC-PTC "size" of the system. The composite PV generation profile could be used in subsequent power flow analyses. This profile is based on the assumed mix of PV system designs summarized in Table 2-3.

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3

Biogas Generation Profiles

The Task 1.1.8 analytical activities and results related to biogas generation resources are summarized in this section.

3.1 Overview

Biogas resources slated for development in the program include landfill bioreactors, animal manure digesters, and enhancement of wastewater treatment plant digesters. The generation profiles estimated for biogas and PV are fundamentally different. Whereas the PV generation profiles described in Section 2 include considerable diurnal and seasonal variation and are sensitive to installation orientation, biogas generation profiles tend to be much flatter. The principal biogas resource characteristics that influence generation profile shapes are summarized below.

3.2 Biogas Resource Characteristics

In the case of all four biogas resources covered by this analysis – landfilled refuse, wastewater treatment plant sludge, cow manure and food processing waste – the *gas production* rate is relatively constant. The per-kWh cost of generating electric energy is therefore minimized by also producing electricity at a constant rate. This operating relationship yields lowest per-kWh electric generating costs because it minimizes or eliminates gas storage costs and costs associated with under-utilized engine-genset capacity. This operating strategy may also tend to minimize costs if steady-state operation maximizes conversion efficiencies, or if constant operation minimizes costs associated with corrosion produced by condensation of acids when biogas-fueled engines are shut down.

Minimizing per-kWh electric generating costs is just one factor contributing to overall project economics. Maximizing per-kWh electric generating benefits is equally important, and may be substantially more complicated. Fundamental to this side of the equation is the per-kWh rate of compensation received for the electric energy production of the biogas system. This compensation may vary considerably depending on the structure of the agreement the biogas system owner has with power purchasers, and depending on the

magnitude of electric generating capacity relative to nearby electric loads the biogas system could supply directly.

If nearby loads are small relative to biogas electric generating capacity (e.g., landfill gas applications) the majority of the electric power is likely to be sold under terms of a traditional power purchase agreement (PPA). To date, the economics of landfill gas projects marketing their power output through PPA have not justified the extra expense associated with gas storage and extra engine-genset capacity necessary to yield highly variable generation profiles.

If nearby electric loads are substantial in comparison to biogas system power output then project economics may be optimized by operating the generator and loads in parallel with the grid. The way this is done may be different for wastewater treatment plants and dairies, because biogas digester facilities utilizing manure may be eligible for a net-metering pilot program signed into law (AB 2228) in September 2002. In the case of wastewater treatment plants, if on-site loads exceed generation then power output of the biogas system is valued at the retail rate of electricity, which is generally higher than the terms that typical power purchase agreements could offer. Biogas systems at wastewater treatment plants are not eligible for net metering. Consequently, if biogas system power output exceeds electric load then excess power sent back to the grid is valued at less than the retail rate for electricity.

If the profile of electric loads on the billing meter shared with the biogas system is highly variable or is skewed toward the utility's higher cost on-peak periods, or if a digester is sited at a dairy and is eligible for net-metering, then investment in gas storage and additional generator capacity may be justified. The economics of gas storage are site-specific and depend on numerous factors, including: the cost of biogas storage, the cost of generator capacity, the retail tariff structure, and the compensation (if any) for net power deliveries to the grid.

In the absence of site-specific design and cost data it is not possible to determine whether or not financial considerations justify the additional expense of biogas storage and additional generator capacity. Therefore, the electric generation profiles for all four biogas digester applications are assumed to be relatively flat. One factor that will contribute a modest measure of variability into the profiles is the influence of ambient temperature on engine or turbine power output. Typical temperature sensitivity relationships for engines and turbines are depicted graphically in Figure 3-1 (EPA 2002).

The data in Figure 3-1 illustrate an important point related to the basis of engine and turbine power output capacities. Namely, they are variable, and manufacturers may quote system sizes based on different ambient temperature conditions. The typical performance characteristics in Figure 3-1 assume that engine size is rated at 77 °F while microturbine size

is rated at 59 °F. The power output of the turbine diminishes from the nominal, rated size more quickly (i.e., 1%/2°F versus 1%/10°F for the reciprocating engine).

Figure 3-1: Ambient Temperature Influence on Power Output
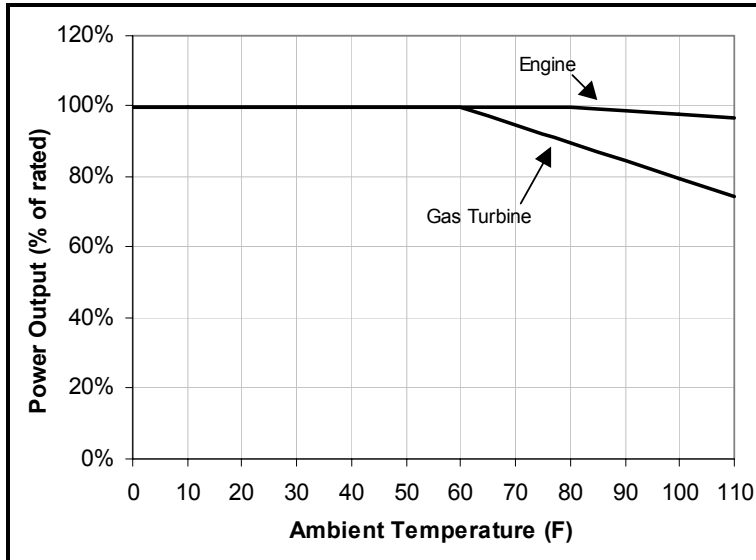
3.3 Results

The generation profiles for all four biogas resources are assumed to vary only as a function of prime mover technology (i.e., engine or turbine). The electric generator systems are assumed to be sized to consume the available biogas flow rate when operating at the ambient temperature used by manufacturers for equipment rating purposes. At elevated ambient temperatures, power output falls according to the relationships summarized in Figure 3-1[1]. Hourly Biogas generation profiles are saved in the MS Access database accompanying this report. A description of the layout of the database is included as Appendix A.

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[1] This assumed design could require flaring of biogas during periods of elevated ambient temperature. An alternate design could entail oversizing of gas turbines. This approach would decrease or eliminate the need for flaring, but would also increase capital costs and require part-load operation during periods of lower ambient temperature.

Annual biogas digester facility electric energy production results are summarized in Table 3-1. [2]

Table 3-1: Annual Electric Energy Production versus Technology

Technology	Annual Energy per kW of Rated Capacity (kWh/Year)
Engine	8,759
Microturbine	8,562

Variability in average seasonal power output is depicted graphically in Figure 3-2 and Figure 3-3. The "Winter" curve is based on data for December through February, while the "Summer" curve is based on data for June through August. In these charts, hour of day is based on clock time as opposed to standard time (i.e., the times represent Daylight Savings Time in the summer).

Figure 3-2: Graphical Summary of Reciprocating Engine Generation Profiles

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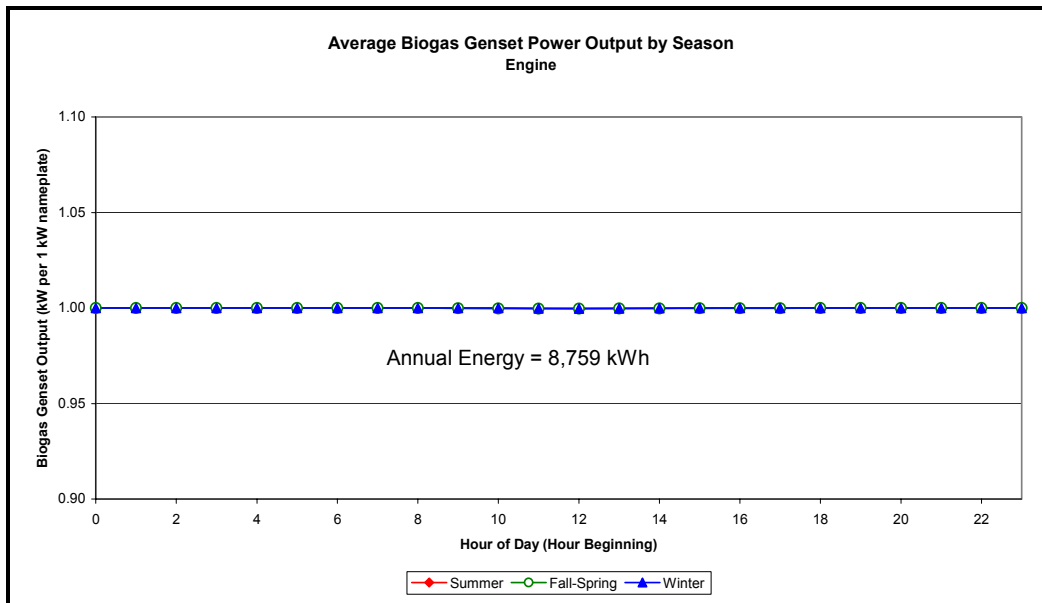
[2] Production downtime has not been taken into consideration. The intent is to illustrate the maximum annual production independent of maintenance related downtime.

Figure 3-3: Graphical Summary of Gas Turbine Generation Profiles
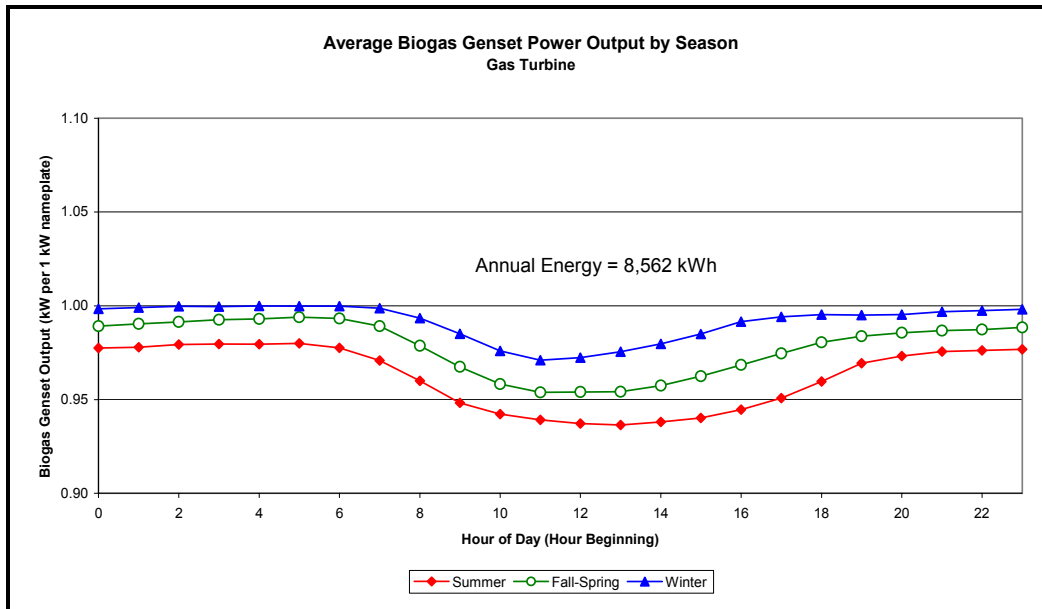
For purposes of supporting subsequent power flow modeling it is necessary to develop a single, composite generation profile for Biogas. The magnitude and shape of the composite generation profile will be directly related to assumptions concerning the mix of conversion technologies for developed projects. Composite characteristics assumed for this analysis are summarized in Table 3-2. Characteristics of systems actually installed through the PIER/Commonwealth program may differ.

Table 3-2: Characteristics of Biogas Composite

Technology	Portion of Mix (%)
Engine	50%
Turbine	50%

A composite Biogas generation profile was calculated using the characteristics summarized in Table 3-2. Results of the analysis are summarized graphically in Figure 3-4. The per-unit annual energy production for the composite generation profile is 8,661 kWh/year per 1.0 kW of rated engine/turbine capacity.

Figure 3-4: Graphical Summary of Composite Biogas Generation Profile
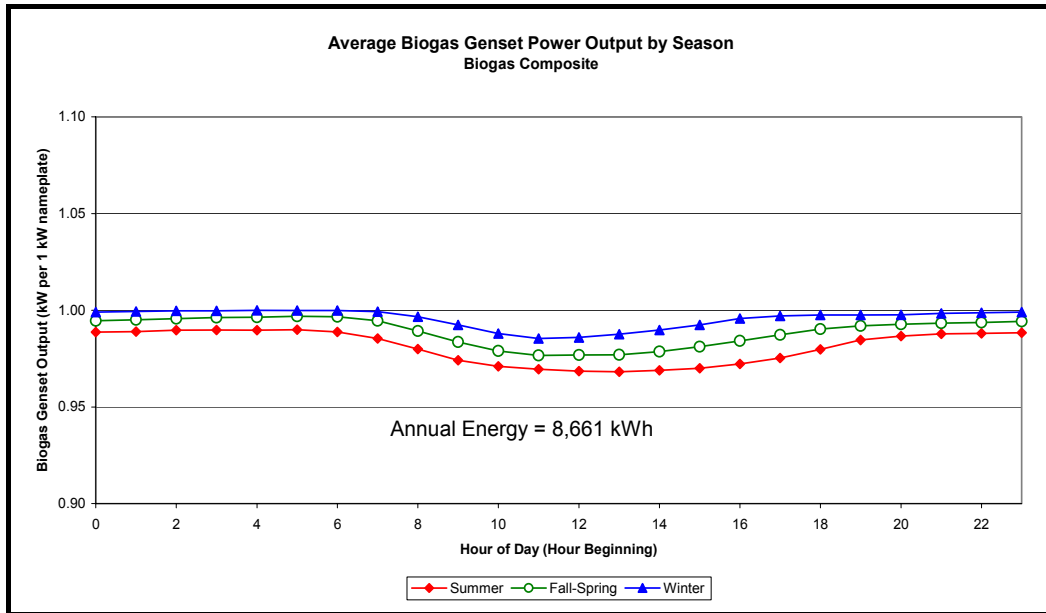
To develop a market-potential composite biogas generation profile for the study period, the shape information illustrated in Figure 3-2 and Figure 3-3 was combined with results of the analysis of market potential magnitude. The combined mini-grid biogas market potential estimated for years 2003 through 2012 ranged from 4.6 MW to 8.3 MW in capacity and from 37,984 MWh to 68,542 MWh in energy generation. Resulting energy production and installed capacity trends for the Market Potential study period are summarized in Figure 3-5.

Figure 3-5: Generation Profile Summary – Chino Mini-grid Biogas Market Potential
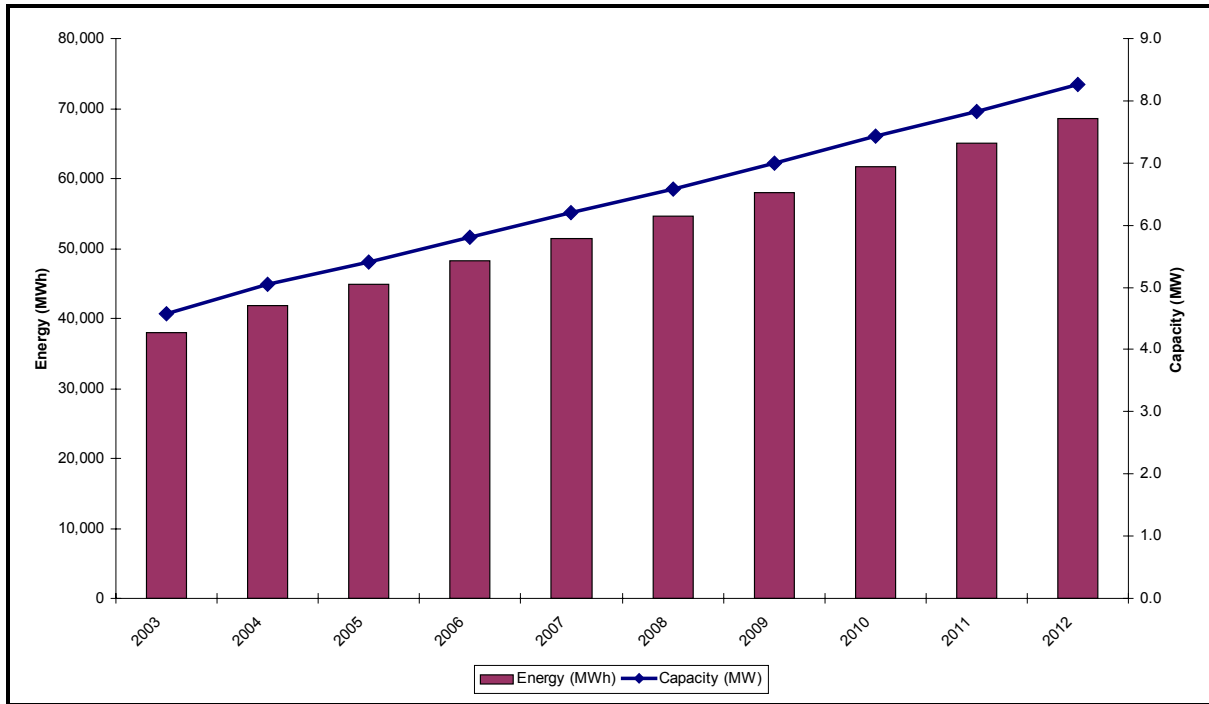
Characteristics of biogas systems actually installed through the PIER Commonwealth biogas programs differ from those presented in Table 3-2. The characteristics of the three biogas systems expected to be installed through the program are summarized in Table 3-3. Each project's size represents the incremental generation over and above any preexisting generation that exists at the project sites.

Table 3-3: System Characteristics – PIER Commonwealth Biogas Progams

Project No.	Description	System Size (kW)	Generation Technology	Start Date
Project 2.1	Landfill Bioreactor Biogas	2,000[3]	MT/Recip. Engine	3/1/05
Project 2.2	Wastewater Treatment Biogas	100	Recip. Engine	5/1/05
Project 3.1	Dairy/Food Processing Waste Biogas	98	MT/Recip.	4/1/05

The energy generation and installed capacity trends corresponding to the combined activities of Projects 2.1, 2.2 and 3.1 under the PIER Commonwealth Program are illustrated in Figure 3-6 for the Program period.

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[3] Landfill bioreactor generation will be staged in over a period of time -- as the biogas production increases and may include a hybrid of on-site generation (retail displacement of existing load at the landfill site via a microturbine) and greater levels of electric generation for wholesale power sale.

Figure 3-6: Generation Profile Summary – PIER Commonwealth Biogas Projects
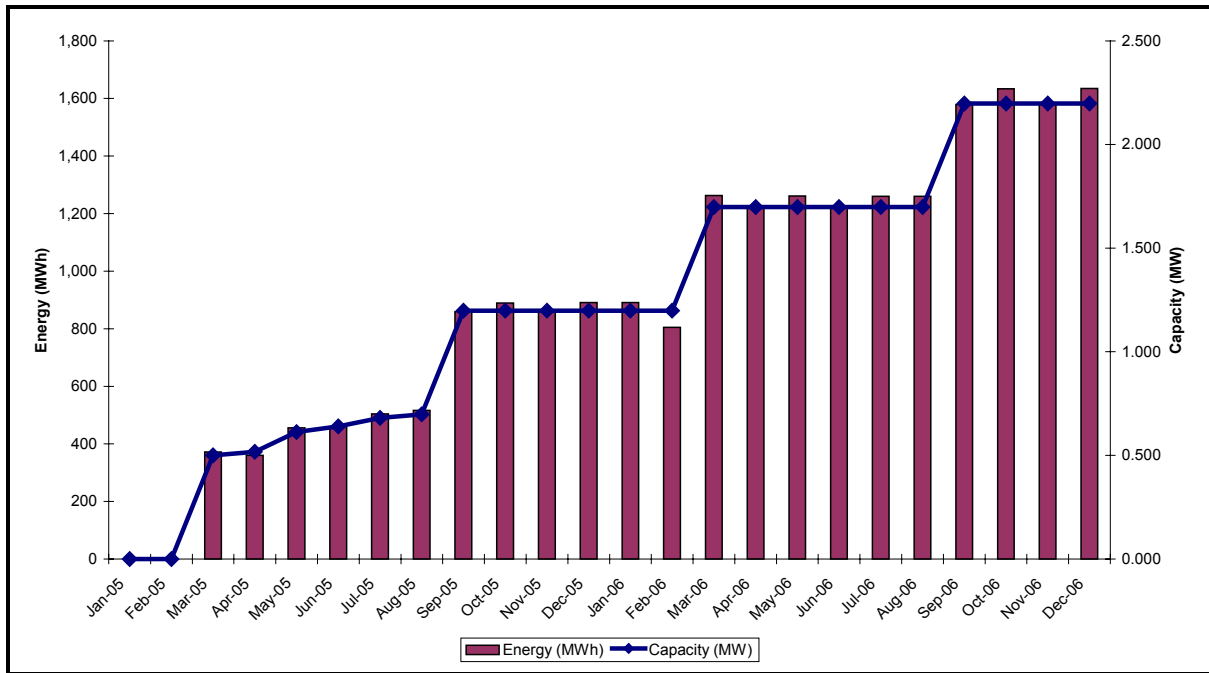
Flexibility of Generation Profiles

There are at least four general ways in which generation profile values could be controlled, thereby increasing flexibility of generation profiles. The rate of production of gas could be varied, the biogas could be used for an alternate use (e.g., flare, delivery to pipeline, use in boiler for space/process heat), gas storage could be included in the system design, or turbines could be oversized. As a practical matter, anaerobic digestion process considerations typically preclude variation of gas production rates solely for the purpose of modifying electric generation profiles. While biogas could be directed toward uses other than electric generation, these alternatives are more likely to be pursued in cases where systems do not include electric generation equipment. Given the presence of electric generation equipment in systems considered by this program, this is not a likely means for controlling/modifying generation profiles.

Three of the four biogas resources use the same basic technology to produce biogas, namely anaerobic digestion. In addition, the focus has been on centralized digesters. Much of the work on centralized digesters has taken place in Denmark. The Danish experience suggests that there is still a need for more RD&D in the area of biogas production in order to make centralized digesters more economical. Reports of technical defects, even on new facilities, leading to operational problems may still be discouraging potential owners. To use biogas for peak or time-of-use (TOU) electric generation, biogas storage technology would need to

be employed. At present, storage of biogas for TOU generation purposes does not appear to have been considered anywhere. That is not to say that biogas storage is not practiced. Storage is utilized as part of the gas collection system more than anything else. Low-pressure storage is common, but high-pressure storage is not. It is not known if economical TOU generation would require or benefit from high-pressure biogas storage. The uncertainties with centralized digester technology for biogas production, not to mention biogas cleaning technology, appear to be great enough that consideration of biogas storage and TOU generation is likely to be beyond the planning horizon of the Commonwealth Program.

Landfill biogas may be a different case when it comes to TOU generation. Landfill gas production is reliable enough where an initial engineering assessment would reveal whether or not this has any possibility of being economical. Such an assessment would be required to answer whether low-pressure storage of biogas would be suitable for TOU generation. However, given the potential biogas production benefits associated with bioreactor technology, RD&D efforts would appear to be better spent here than on biogas storage and TOU generation.

A larger market consideration to the flexibility of all these resources has to due with the dispatchability of the generation. To take advantage of TOU pricing, the generation needs to function in one of two ways. The first is that nearly all the generation be supplied back to the grid and that it be dispatchable by the Independent System Operator (ISO). Currently, generation contracts for renewable resources are fixed price contracts. Historically, the structure of power purchase agreements has been a limiting factor. Only if the technology has proven itself to be reliably dispatched will that technology be able to take advantage of hourly system prices. Generally, fossil fueled generators are hundreds of megawatts or larger in size where as renewable generators are much smaller. It is uncertain that small generators would be desirable as a dispatchable resource for anything other than emergency conditions. The economics from a system dispatch perspective are not likely to be favorable in the near future.

The second method of operation is that the electricity produced not exceed the owner's load at the same premises as the generator. In this instance, the generator power output does not need to be variable to take advantage of TOU pricing. As long as the renewable generation is offsetting a portion of the customer load at peak hours then it is effectively being priced at TOU rates. It is generally not economic for PV generated electricity to be stored to serve load at low priced off-peak hours. It is not known whether biogas generation would be economic under this arrangement since the generation would likely be small and not able to take advantage of economies of scale. The generation profiles for turbine based facilities could be flattened by increasing turbine size. This approach would require operation at

partial load during many cooler hours of the year, however, which could decrease average conversion efficiency, and would increase operationg costs.

Given the naturally occurring load following nature of PV electric generation, it may be more economical to pursue the ancillary benefits associated with biogas production (e.g., reduced ground water contamination, reduced GHG, fertilizer by-products, etc.) and the improvement of biogas production before pursuing any enhancements generation profile enhancements. The PV technical potential in the mini-grid is larger than the entire load in the area. As far as a fully realized mini-grid, utilizing a mix of resources whose least cost implementation provides base load (biogas) on the one hand and load following (BI-PV) on the other would appear to be the most logical approach.

3.4 Discussion of Results

Key aspects of the assumptions, analytic methods, and results are described briefly below.

Landfill Gas Production Lifecycle

Landfill gas generation is estimated to begin from six months to two years after waste is placed in a landfill. Gas generation rates vary depending on moisture content and other site-specific factors. The basic pattern is that landfill gas generation rates are highest in the two years after waste has been filled. During this time, anaerobic digestion of most of the degradable content of food wastes occurs. LFG generation continues after this time but at slowly decreasing rates. While gas generation rates can extend for periods of up to fifty years, in most cases primary gas release occurs within the first 10 years.

Storage of landfill gas on a large scale is not generally considered economically practicable. The generation profile for landfill gas applications is therefore a function of gas collection/conversion equipment size relative to gas generation rates. Landfill gas collection systems are typically sized to satisfy gas collection and combustion requirements when gas generation rates are at their highest. Energy conversion equipment (e.g., engines, gas turbines) used for landfill gas applications is typically sized such that it can operate continuously for 10 years without having to increase or decrease power output due to changes in landfill gas generation rates. Operation in this manner dictates that during some periods of power plant life some of the landfill gas must bypass the energy conversion system. Landfill gas that is bypassed in this manner is typically flared.

3.5 Conclusions

Biogas generation profiles impacting the electric distribution system are intertwined with a variety of economic factors influencing biogas system design and operation. As a first-order

approximation, the generation profiles for all four biogas resources – landfill refuse, wastewater treatment sludge, dairy cow manure and food processing waste – are relatively flat. Refinement of these current generation profiles is contingent upon refinement of available information related to technology implementation and these biogas resource utilization drivers in the Chino basin.

References

Technology Characterization: Microturbines, Prepared by Energy Nexus Group for the US Environmental Protection Agency, Climate Protection Partnership Division, March 2002.

Technology Characterization: Reciprocating Engines, Prepared by Energy Nexus Group for the US Environmental Protection Agency, Climate Protection Partnership Division, February 2002.

Appendix A

Generation Profiles Database Guide

The MS Access database accompanying this report contains hourly PV and biogas generation profile values. Generation profiles for 104 different tilt-orientation-material-tracking combinations are included in the 'PV' table. Fields in the PV table are described in Table A-1.

Table A-1: Fields in the MS Access PV Generation Profiles Table

Field Name	Values	Description
ProfType	Flat, Fixed, 1-axis, 2-axis, Program, Market	Generation Profile Type. 'Program' refers to BI-PV capacity installed under the Commonwealth program through 2006. 'Market' refers to BI-PV market potential in 2012; these data express both the shape and magnitude of BI-PV generation profiles.
Material	Crystal, Amorph	PV Material Type. 'Crystal' for crystalline silicon PV, 'Amorph' for amorphous silicon PV. 'N/A' for composite generation profiles.
M_LDT	1 to 12	Month of year, local daylight time.
D_LDT	1 to 31	Day of month, local daylight time.
H_LDT	0 to 23 by 1	Hour of day (hour beginning), local daylight time.
Tilt	0 to 90 by 30	Array tilt in degrees from horizontal.
Azimuth	0 to 315 by 15	Array azimuth in degrees, South 0, West positive, East negative.
DBT	4.4 to 35.0	Ambient Dry Bulb Temperature, ºC
GHR	0 to 1024	Global Horizontal Radiation, Watts/m^2
I_t	0 to 1114	Total Plane-of-Array Radiation, Watts/m^2
PWR	0 to	Hourly average power output.
Units	kW, kW/kW	'kW/kW' is used to express the shape element of generation profiles (i.e., hourly average kW produced by a 1.0 kW AC-PTC PV system).

Generation profiles for biogas engine- and turbine-gensets are included in the 'BIOGAS' table. Fields in the BIOGAS table are described in Table A-2.

Table A-2: Fields in the MS Access Biogas Generation Profiles Table

Field Name	Values	Description
ProfType	ICE, Turbine, Program, Market	Generation Profile Type. 'Program' refers to biogas capacity installed under the Commonwealth program through 2006. 'Market' refers to biogas market potential in 2012; these data express both the shape and magnitude of BI-PV generation profiles.
M_LDT	1 to 12	Month of year, local daylight time
D_LDT	1 to 31	Day of month, local daylight time
H_LDT	0 to 23	Hour of day (hour beginning), local daylight time
DBT	4.4 to 35.0	Ambient Dry Bulb Temperature, ºC
PWR	0 to 1.0	Hourly average power output for a 1.0 kW AC Biogas system (Basis: nameplate system size)
Units	kW, kW/kW	'kW/kW' is used to express the shape element of ICE and Turbine generation profiles (i.e., hourly average kW produced by a 1.0 kW system).